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P.I.: Janet G. Luhmann, UCLA Institute of Geophysics and Planetary Physics
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Summary of Accomplishments

The purpose of this VDAP investigation has been to bring together selected Pioneer Venus Orbiter (PVO) plasma and field data sets in order to derive the maximum information relating to ion scavenging from Venus by the solar wind interaction. Understanding derived from these observational analyses can be used to infer the evolutionary importance of such loss processes at this weakly magnetized planet. To make such inferences, it is necessary to understand the physics of the escape sufficiently well to model it under conditions of solar radiation and solar wind conditions expected for the early Sun. The plan was to attack this problem from several directions, first analyzing selected PVO observations of escaping ions and then modeling the escape process globally.

While completion of the originally proposed work was curtailed somewhat by early cancellation of the VDAP program, significant progress was made toward our original goals. In particular, we applied our earlier model that views the Venus ionospheric "tail rays" as escaping ions to the interpretation of atomic and molecular ion flows observed with the PVO neutral mass spectrometer in its ion mode. We worked with Oleg Vaisberg of IKI, and Sean Kilpatrick, undergraduate at UCLA, to complete a survey of all energetic O+ ion detections by the PVO plasma analyzer during the PVO mission, and we discovered, by extending the tail ray model to the distant wake, that the energetic ions are most likely the tail rays further downstream rather than a separate population of pickup ions from the extended oxygen corona. This finding affects our assessment of the total escape rate since it was previously considered that there was an "unseen" escaping low energy, low altitude component and a second coronal component that the plasma analyzer detected. Now it seems that the Langmuir probe observed the unseen component as the near-periapsis wake tail rays, and then the plasma analyzer detected them after they were accelerated by the solar wind enroute to the apoapsis distance. The rate of O+ escape derived from the PVO observations is thus a reflection of the more concentrated "cold" exospheric source rather than the greatly extended "hot" coronal source. The extended source, though it contributes a significant fraction to the total loss when integrated globally, evidently produces O+ fluxes too low to have been measured on the PVO spacecraft. The understanding of this distinction will help in the interpretation of escaping ion observations at Mars on Mars-96 and Planet-B, as well as in evaluations of historical escape rates.

The related work that remains is the publication of the results on the tail ray origin of the Venus energetic O+ wake, and application of this new understanding of the sources of the escaping ions to evolutionary scenarios. Publications generated during the course of this project are listed below and described in the appended abstracts.

References

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Patents or Inventions Resulting

None.

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The inner magnetosheath of Venus: An analogue for Earth?

J. G. Luhmann[1]

Institute of Geophysics and Planetary Physics, University of California, Los Angeles

Abstract. The unmagnetized planets provide examples of solar wind interactions that are free from the complications associated with magnetopause reconnection and with sensitive obstacle response to incident solar wind pressure changes. Using the Venus magnetosheath as a testbed, we search for evidence of standing slow mode "transitions" in the inner subsolar region as reported for Earth by Song et al. [1990a; 1992a; b]. Although the system at Venus is much smaller in scale, the Pioneer Venus Orbiter magnetometer data indicate that for perpendicular interplanetary magnetic field conditions the general behavior of the plasma in the magnetosheath is as expected from the simple depletion layer model. In examples of magnetic field measurements chosen for the apparently steady interplanetary conditions during the spacecraft pass, there is no clear evidence for a slow mode structure near the ionopause as might be expected on the basis of the Song et al. study. The implication is that some aspect of the Venus magnetosheath (such as its small size or the presence of local planetary ion production) makes it physically different from Earth's, that the conditions of the magnetosheath during Song's study differed significantly from those in the Venus study, or that the observations of Song et al. do not represent a steady state.

Introduction

One of the major difficulties associated with the observational study of processes occurring in the Earth's magnetosheath near the magnetopause is that the magnetized magnetosheath plasma reconnects with the magnetic field of the magnetospheric obstacle. The Earth's magnetosheath is also large enough to make the identification of steady conditions difficult, as solar wind plasma and field variations occur on timescales much smaller than spacecraft transit times through the subsolar region. Moreover, the magneto-sphere is a highly "compressible" obstacle so that the magnetopause position is a sensitive function of incident solar wind dynamic pressure. Recently, *Song et al.* [1990, 1992a, b] published several papers reporting the existence of a newly identified region in the inner magnetosheath which they call a "slow mode transition." Earthward of its outer boundary, indicated in the reproduced example in Figure 1, an unsteady density enhancement is observed oscillating in antiphase with low-frequency magnetic field fluctuations [*Song et al.*, 1992a]. This region occurs just outside of the depletion layer in the inner magnetosheath [e.g., *Zwan and Wolf*, 1976; *Crooker et al.*, 1979]. It appears most prominent for low plasma beta (≤ 1) conditions [*Song et al.*, 1990a]. *Southwood and Kivelson* [1992] make theoretical arguments in support of *Song et al.*'s [1992a] suggstion that such a transition region is present because the stationary subsolar magnetopause can create a standing slow mode structure. The waves associated with the structure affect the oncoming solar wind flow and field, reorienting them to directions tangent to the magnetopause inside of the transition. They also suggest, as illustrated by Figure 2, that for a perpendicular interplanetary field a general distortion of the inner magnetosheath field draping occurs in the transition.

Song et al. [1992a] point out that in previous MHD models of the solar wind interaction with an impenetrable obstacle [e.g., *Zwan and Wolf*, 1976], the transition to tangent flow within the magnetosheath is considered to occur in a gradual and continuous fashion. This implies that the MHD forces causing the flow and field deviations are distributed as opposed to localized in the region of the depletion layer. Recent numerical models of three-dimensional MHD flow around a conducting body by *Molvik et al.* [1991], *Wu* [1992], and *Tanaka* [1993] seem to support the picture of smooth transitions of the plasma and field parameters throughout the magnetosheath. Thus there is an apparent disagree-ment concerning the existence of a distinct standing slow mode structure adjacent to the inner boundary, although it must be recognized that these models in general assume isotropic pressure. (Because of this assumption, the model depletion process does not include the physics associated with the growth of pressure or beta anisotropies.)

One potentially useful space plasma "laboratory" experiment for magnetosheath studies is the solar wind interaction with unmagnetized planets (e.g., see the reviews by *Luhmann* [1986] and by *Luhmann and Brace* [1991]). These interactions are free of complications produced by magnetic reconnection with an intrinsic planetary field and have other advantages as well. The solar wind interacts directly with the ionosphere, where the counterpart of the Chapman-Ferraro current system flows. Since the pressure balance of the incoming plasma is with the planetary

[1]Also at Space Sciences Laboratory, University of California, Berkeley.

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On removing molecular ions from Venus

J. G. Luhmann[1]
Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California

W. T. Kasprzak and J. M. Grebowsky
NASA Goddard Space Flight Center, Greenbelt, Maryland

Abstract. Acceleration or "pickup" of exospheric atomic oxygen ions by the interplanetary convection electric field is a generally accepted mechanism for the observed removal of O^+ from Venus. However, heavier escaping molecular ions (e.g., O_2^+, CO_2^+, N_2^+, CO^+, and NO^+) in high abundances were also detected in the wake by the Pioneer Venus Orbiter (PVO) neutral mass spectrometer (ONMS) operating in its ion mode. It was recently demonstrated that pickup of O^+ at low velocities from the terminator upper ionosphere could explain some characteristics of the Venus ionospheric "tail rays." Since the PVO ion mass spectrometer data indicate that a significant molecular ion component also contributes to the terminator ionosphere above the collisional region ($\geq$ 250 to 300 km altitude), we apply the tail ray model to study both the associated low-altitude O^+ flows and the behavior of heavier ions of similar origin. The predicted flow vectors show dawn/dusk asymmetries similar to those in the ONMS observations. Further, the heavier ions achieve higher peak energies, thus improving their chances of detection by the ONMS which has an energy threshold of $\sim$36 eV in the spacecraft frame. The appeal of this explanation is that no exotic or complicated interpretations are required, and that a broad set of diverse observations fit a common scenario. The same mechanism could in principle be operating at Mars where molecular ions were also detected in the wake on Phobos 2.

Introduction

It was recently proposed [*Luhmann*, 1993] that the Venus wake structures known as ionospheric tail rays [*Brace et al.*, 1987] can result from the penetration of the solar wind convection electric field into the oxygen-dominated high (>250 km) altitude terminator ionosphere. At altitudes where collisions are infrequent the electric field maps along the inner magnetosheath field lines threading the upper ionosphere. There it can become the dominant force, exceeding the antisolar pressure gradient force that drives day-to-night transport at lower altitudes. In this case the upper ionosphere ions can be accelerated or "picked up" by the same physical mechanism that leads to solar wind scavenging of the O^+ ions created in the high-altitude exosphere. While the exospheric ions are accelerated to high (> 1 keV) energies and thus exhibit marked asymmetries controlled by the solar wind convection electric field due to their large gyroradii [e.g., *Phillips et al.*, 1987; *Intriligator*, 1989; *Moore et al.*, 1990], the picked up upper ionosphere ions have low ($\sim$ 10s of eV) energies and show insignificant finite gyroradius effects mirroring the low local flow speeds and compressed, draped magnetic field. This concept is of interest both because it obviates the need to invoke other, more exotic planetary ion pickup processes to explain the tail rays, and also because it allows us to more simply and accurately estimate the solar wind scavenging rate. However, it also has implications for other observations obtained on the Pioneer Venus Orbiter (PVO).

Here we show that the same model can account for the properties of Venus' nightside superthermal ion flows as detected by the PVO neutral mass spectrometer (ONMS) in its ion mode of operation [*Kasprzak et al.*, 1982, 1987, 1991], including the vector magnitudes and directions and the abundances of heavy molecular ions in those flows. If the ONMS ion flows are regarded as tail ray ions observed at low altitudes, the observed dawn/dusk asymmetries in the flow pattern can be understood in terms of the effect of the average interplanetary magnetic field draping pattern. Moreover, the escape of heavy molecular ions is a natural consequence of their regular presence in the collisionless region of the terminator upper ionosphere where they are exposed to the same accelerating field as the O^+. This model should in principle apply to any unmagnetized planet having an ionosphere, including Mars, where ionospheric atomic and molecular ions were similarly observed in the low-altitude wake on the Phobos 2 spacecraft [*Lundin et al.*, 1990].

[1]Now at Space Sciences Laboratory, University of California, Berkeley.

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Structure of the Venus Tail

O. Vaisberg, V. Smirnov, A. O. Fedorov, L. Avanov, and F. Dunjushkin

Space Research Institute, Moscow, Russia

J. G. Luhmann and C. T. Russell

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, USA

The steady-state tail of Venus at relatively close distances to the planet consists of two magnetic field lobes separated by a current sheet. It is believed to be formed by the mass loading of passing solar wind magnetic flux tubes by planetary ions. The lobes are separated by a current sheet presumably populated by hot plasma. The induced magnetic tail together with the cross-tail current sheet rotates around its axis due to rotation of the transverse component of the IMF. The magnetic field structure in the tail at 10-12 R_v downstream is always very complicated and shows a variety of magnetic structures and current layers. This appearance is usually interpreted in terms of motions of the tail.

Within the Venusian tail at close and intermediate downstream distances (from 0.5 R_v to ~ 5 R_v) Venera 9 and 10 measured relatively low-energy ion fluxes that appear to be nearly permanent. At least two plasma populations were identified: one within the tail lobes, and another more energetic one at the current layer. Pioneer Venus data also indicated the presence of two ion populations in the tail at ~ 10-12 R_v, with the higher energy population being interpreted as accelerated planetary oxygen ions. In this report we analyze different plasma regimes in the context of the observed magnetic field configurations in the tail.

INTRODUCTION

Venus is the most extensively studied case of the solar wind interaction with a non-magnetized planet. The ionosphere and upper atmosphere of the planet form an almost impenetrable obstacle to the solar wind flow. As a result, a bow shock forms that heats and deflects the supersonic solar wind plasma around the planet. The shocked solar wind plasma, while flowing around the planet, interacts with newly born ions from the upper atmosphere. The pick-up of newly born ions leads to significant modification of the flow close to the planet, and determines the configuration and properties of the Venus tail.

Solar System Plasmas in Space and Time
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The data on the solar wind-Venus interaction were collected mostly by Venera 9 and 10 in 1975-1976 and by Pioneer Venus Orbiter (PVO) from 1978-1992 [see *Russell and Vaisberg*, 1983; *Phillips and McComas*, 1991, for reviews]. It was shown that Venus has an induced magnetic tail with two magnetic lobes formed by draping of interplanetary magnetic field (IMF) around the planet [*Yeroshenko*, 1979]. Distinct changes of the plasma regime from ionosheath flow to antisunward low-energy plasma flow in the tail were found at close downstream distances [*Vaisberg et al.*, 1976].

The purpose of this paper is to summarize existing plasma observations within the Venusian tail. We will consider plasma domains observed at different distances and within different magnetic field configurations, dynamics of the tail plasma, the possible connections between the plasma properties and magnetic field structures in the tail, and will

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ION POPULATIONS IN THE TAIL OF VENUS

O. Vaisberg,* A. Fedorov,* F. Dunjushkin,* A. Kozhukhovsky,* V. Smirnov,* L. Avanov,* C. T. Russell** and J. G. Luhmann**

* *Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, Moscow 117810, Russia*
** *Institute of Geophysics and Planetary Physics, University of California at Los Angeles, Los Angeles, CA 90024-1567, U.S.A.*

ABSTRACT

Plasma measurements in the tails of Venus showed the existence of several ion populations. Measurements performed on Venera and Pioneer Venus spacecraft at different planetocentric distances showed the evolution of the plasma parameters along the tail. Low-energy ion fluxes measured in the tail at close downstream distances, are also observed farther downstream, and show low acceleration from 0.5 R_V to 12 R_V. High energy ions (energetic O^+ ions) reported from PVO observations in the tail at 10-12 R_V seem to be the same ion component that was observed as energetic ions at the tail boundary close to the planet have on Venera spacecraft. We give evidences that these ions are accelerated in the narrow shear layer near the tail boundary.

INTRODUCTION

Venus is the most extensively studied case of the solar wind interaction with a non-magnetized planet. The solar wind-Venus interaction was mainly studied on Venera 9 and 10 in 1975-1976 /1-3 / and on Pioneer Venus Orbiter (PVO) in 1978-1992 [see /4 - 7/ for reviews]. We summarize existing plasma observations within the Venusian tail and discuss the origin of the tail plasma.

PLASMA WITHIN THE TAIL

Plasma instruments flown. The Venera 9 and 10 satellites had two plasma spectrometers: a 2-D ion spectrometer consisting of 6 narrow-angle cylindrical electrostatic analyzers with channel electron multipliers (CEMs) RIEP /8/ and a combination sunward-looking differential ion Faraday cup and antisunward oriented integral electron Faraday cup D-127 /9/. The energy ranges were: 50 eV/Q to 20 keV/Q (RIEP) and 0-4 keV/Q for ions and 0-400 eV for electrons (D-127). The temporal resolution of both spectrometers was 160 sec. Measurements of plasma and magnetic field on Venera 9 and 10 within the tail from approximately 0.5 Rv behind the terminator to about 5 Rv downstream were performed on selected orbits in October 1975- March 1976 . The 3-D PVO plasma analyzer /10/ was of the quadrispheric electrostatic type with five collectors. The energy per unit charge (E/Q) range from 50 to 8000 eV/Q was scanned in 9 minutes. PVO operated in orbit around Venus